“This book provides an in-depth introduction to radio resource management (RRM) in wireless networks. Through various practical examples, it demonstrates how to model and analyze RRM problems and optimize wireless network performance. It is an outstanding textbook for graduate students and an excellent scholarly reference for engineers and researchers.”

Geoffrey Li, Georgia Institute of Technology
Radio Resource Management in Wireless Networks
An Engineering Approach

Do you need to design efficient wireless communications systems? This unique text provides detailed coverage of radio resource allocation problems in wireless networks and the techniques that can be used to solve them. Covering basic principles and mathematical algorithms, with a particular focus on power control and channel allocation, you will learn how to model, analyze, and optimize the allocation of resources in both physical and data link layers for a range of different network types. Both established and emerging networks are considered, including CDMA and OFDMA wireless networks, relay-based wireless networks, and cognitive radio networks. Numerous exercises help you put knowledge into practice and provide the tools needed to address some of the current research problems in the field.

This is an essential reference whether you are a graduate student, researcher, or industry professional working in the field of wireless communication networks.

Ekram Hossain is a Professor in the Department of Electrical and Computer Engineering at the University of Manitoba, and a Fellow of the IEEE. He is the co-author or co-editor of several books, including Wireless Device-to-Device Communications and Networks (Cambridge, 2015) and Smart Grid Communications and Networking (Cambridge, 2012).

Mehdi Rasti is an Assistant Professor in the Department of Computer Engineering and Information Technology at the Amirkabir University of Technology in Iran. He previously worked at the Shiraz University of Technology (Iran) and the Wireless@KTH Royal Institute of Technology (Sweden).

Long Bao Le is an Associate Professor in the National Institute of Scientific Research (Energy, Materials, and Telecommunications) at the University of Quebec.
Radio Resource Management in Wireless Networks
An Engineering Approach

EKRAM HOSSAIN
University of Manitoba

MEHDI RASTI
Amirkabir University of Technology

LONG BAO LE
University of Quebec
## Contents

**Preface**

**Part I Basics of Wireless Networks**

1 **Introduction**
   1.1 Basics of a Wireless Communication System
      1.1.1 Electromagnetic Spectrum and Frequency Range
      1.1.2 Signal Characterization
      1.1.3 Modulation
      1.1.4 Wireless Channel and Signal Propagation
      1.1.5 Channel Capacity
      1.1.6 SINR and Channel Model for Packet Communication Systems
   1.2 Medium Access in Wireless Networks
      1.2.1 Channel Partitioning–Based MAC
      1.2.2 Random Access–Based MAC
      1.2.3 Duplexing
   1.3 Wireless Access Technologies
      1.3.1 Cellular Wireless Technology
      1.3.2 WLAN, WMAN, and WPAN Technologies
   1.4 Exercises
   References

2 **Wireless Networks and Resource Allocation**

   2.1 Protocol Layers for Data Communication
      2.1.1 Physical Layer
      2.1.2 Data Link Layer
      2.1.3 Network Layer
      2.1.4 Transport Layer
      2.1.5 Session, Presentation, and Application Layers
   2.2 Classification of Wireless Networks
      2.2.1 Classification Based on Infrastructure
      2.2.2 Classification Based on Spectrum Access
      2.2.3 Classification Based on Heterogeneity

page xiii
Contents

2.3 Physical Layer Issues in Wireless Networks 56
  2.3.1 Basic Components 56
  2.3.2 Digital Transmission Techniques 58
  2.3.3 Link Adaptation 62
  2.3.4 Diversity Transmission Techniques 65
  2.3.5 Smart Reception/Diversity Combining Techniques 65

2.4 Radio Link Layer Issues in Wireless Networks 68
  2.4.1 Multiple Access and Scheduling Methods 68
  2.4.2 Error Control Methods 93
  2.4.3 Power Control Methods 99
  2.4.4 Cell Association, Handoff Management, and Admission Control 102

2.5 Taxonomy of Resource Allocation 105

2.6 Exercises 106

References 110

Part II Techniques for Modeling and Analysis of Radio Resource Allocation Methods in Wireless Networks

3 Optimization Techniques 117

  3.1 Basics of Optimization 117
    3.1.1 Convex Functions 117
    3.1.2 Optimality Conditions for Unconstrained Optimization 119
    3.1.3 Line Search Methods for Unconstrained Optimization 121

  3.2 Convex Optimization 123
    3.2.1 Introduction 123
    3.2.2 Duality 124
    3.2.3 KKT Conditions 125
    3.2.4 Algorithms 127

  3.3 Integer Programming 132
    3.3.1 Cutting Plane Method 132
    3.3.2 Branch and Bound Algorithm 135

  3.4 Stochastic Optimization 140
    3.4.1 Introduction 140
    3.4.2 Robust Optimization 141

  3.5 Dynamic Programming 143
    3.5.1 Introduction 143
    3.5.2 Examples of Dynamic Programming 145

  3.6 Exercises 147

References 153

4 Game Theory 154

  4.1 Fundamentals of Game Theory 154
    4.1.1 Brief History 154
Contents

4.1.2 Definition of a Game 155
4.2 Non-cooperative Game 159
  4.2.1 Static Game 159
  4.2.2 Dynamic Game 162
  4.2.3 Bayesian Game 166
  4.2.4 Evolutionary Game 168
4.3 Cooperative Game 172
  4.3.1 Nash Bargaining Solution 172
  4.3.2 Coalition Game 174
4.4 Auction Theory 178
  4.4.1 Introduction to Auction Theory 178
  4.4.2 Special Auction 180
4.5 Exercises 182
References 186

Part III Physical Layer Resource Allocation in Wireless Networks

5 General System Model and Preliminary Concepts 191
  5.1 System Model for a General Multi-Cell Wireless Network 191
    5.1.1 Modeling Path-Gains 192
    5.1.2 SINR Model 194
    5.1.3 Transmit Power Vector Corresponding to a Given SINR Vector 195
  5.2 System Model for a Single-Cell Wireless Network 198
    5.2.1 Modeling Path-Gains 198
  5.3 SINR Feasibility in Interference-Limited Wireless Networks 200
    5.3.1 Existence of a Positive Transmit Power Vector Corresponding to a Given SINR Vector 201
    5.3.2 Existence of a Constrained Transmit Power Vector Corresponding to a Given SINR Vector 203
  5.4 Exercises 205
References 206

6 Power Control in Cellular Wireless Networks 207
  6.1 Objectives of Power Control 207
    6.1.1 Performance Measure and Objective Functions 208
    6.1.2 Distributed Versus Centralized Approach 210
  6.2 Different Power Control Optimization Problems 210
  6.3 Closed-Loop and Open-Loop Power Control 215
    6.3.1 Open-Loop Power Control 215
    6.3.2 Closed-Loop Power Control 216
  6.4 Distributed Power Control Algorithms 216
    6.4.1 Criteria for Evaluation and Analysis of Distributed Power Control 217
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4.2</td>
<td>Existing Theoretical Frameworks for Fixed-Point and Convergence Analysis</td>
<td>217</td>
</tr>
<tr>
<td>6.5</td>
<td>Distributed Target-SINR Tracking Power Control (TPC)</td>
<td>220</td>
</tr>
<tr>
<td>6.6</td>
<td>Distributed Opportunistic Power Control (OPC)</td>
<td>222</td>
</tr>
<tr>
<td>6.7</td>
<td>Distributed Dynamic Target-SINR Tracking Power Control (DTPC)</td>
<td>223</td>
</tr>
<tr>
<td>6.8</td>
<td>Exercises</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>230</td>
</tr>
<tr>
<td>7</td>
<td>Distributed Joint Power and Admission Control</td>
<td>231</td>
</tr>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>231</td>
</tr>
<tr>
<td>7.2</td>
<td>Distributed Joint Power and Admission Control Algorithms</td>
<td>233</td>
</tr>
<tr>
<td>7.2.1</td>
<td>TPC with Permanent Removal (TPC-PR)</td>
<td>233</td>
</tr>
<tr>
<td>7.2.2</td>
<td>TPC with the Capability of Temporary Removal (TR)</td>
<td>234</td>
</tr>
<tr>
<td>7.2.3</td>
<td>TPC with Both Temporary and Permanent Removal (TPC-TPR)</td>
<td>235</td>
</tr>
<tr>
<td>7.2.4</td>
<td>TPC with the Capability of Temporary Removal and Feasibility Check (DFC)</td>
<td>235</td>
</tr>
<tr>
<td>7.2.5</td>
<td>TPC with Soft Removal (TPC-SR)</td>
<td>239</td>
</tr>
<tr>
<td>7.3</td>
<td>Exercises</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>244</td>
</tr>
<tr>
<td>8</td>
<td>Joint Power and Admission Control in Cognitive Radio Networks</td>
<td>245</td>
</tr>
<tr>
<td>8.1</td>
<td>Introduction</td>
<td>245</td>
</tr>
<tr>
<td>8.2</td>
<td>System Model and Background</td>
<td>246</td>
</tr>
<tr>
<td>8.3</td>
<td>Protection Constraints for Primary Users and Different JPAC Problems in CRNs</td>
<td>249</td>
</tr>
<tr>
<td>8.4</td>
<td>Characterization of Feasible Interference Region</td>
<td>251</td>
</tr>
<tr>
<td>8.4.1</td>
<td>Total Received-Power-Temperature: Expressing PUs’ Protection Constraints Based on FRPR</td>
<td>252</td>
</tr>
<tr>
<td>8.4.2</td>
<td>Total Inter-Cell Interference Temperature: Expressing PUs’ Protection Constraints Based on FIIR</td>
<td>253</td>
</tr>
<tr>
<td>8.4.3</td>
<td>Total Cognitive Interference Temperature: Expressing PUs’ Protection Constraints Based on FCIR</td>
<td>255</td>
</tr>
<tr>
<td>8.4.4</td>
<td>Example and Discussion</td>
<td>257</td>
</tr>
<tr>
<td>8.5</td>
<td>Existing Centralized JPAC Algorithms to Maximize the Number of Supported SUs Subject to PUs’ Protection Constraint</td>
<td>259</td>
</tr>
<tr>
<td>8.5.1</td>
<td>A General SSA</td>
<td>260</td>
</tr>
<tr>
<td>8.5.2</td>
<td>Interference Constraint-Aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA)</td>
<td>263</td>
</tr>
<tr>
<td>8.5.3</td>
<td>Link-Gain Ratio Algorithm (LGRA) and Effective Link-Gain Ratio Algorithm (ELGRA)</td>
<td>264</td>
</tr>
<tr>
<td>8.6</td>
<td>Distributed JPAC Algorithms for CRNs</td>
<td>267</td>
</tr>
<tr>
<td>8.6.1</td>
<td>TPC with PU-Protection Algorithm (TPC-PP)</td>
<td>267</td>
</tr>
<tr>
<td>8.6.2</td>
<td>Improved TPC-PP (ITPC-PP)</td>
<td>270</td>
</tr>
</tbody>
</table>
## Contents

8.7 Exercises 271  
References 274

9 Cell Association in Cellular Networks 276  
9.1 Introduction 276  
9.2 System Model and Notations 276  
9.3 Distributed Joint Cell Association and Power Control 278  
9.4 Distributed Cell Association Schemes in Wireless Networks 281  
9.4.1 Reference Signal Received Power (RSRP)-Based Cell Association Scheme 281  
9.4.2 Biasing-Based Cell Range Expansion (CRE) in Wireless Networks with Heterogeneous BSs 282  
9.5 Open Research Issues 284  
9.6 Exercises 286  
References 287

Part IV Link Layer Resource Allocation in Wireless Networks  
10 Sub-Carrier/Sub-Channel Allocation in OFDMA Networks 291  
10.1 Introduction 291  
10.2 OFDM-Based Multiple Access 292  
10.3 Adaptive Radio Resource Allocation in OFDM Systems 293  
10.3.1 System-Centric Approaches 294  
10.3.2 Application-Centric Approaches 302  
10.4 Open Research Issues 303  
References 304

11 Resource Allocation in Relay-Based Networks 308  
11.1 Introduction 308  
11.2 Overview of Cooperative Diversity 309  
11.2.1 Amplify-and-Forward Relaying 309  
11.2.2 Decode-and-Forward Relaying 310  
11.2.3 Selection or Opportunistic Relaying 311  
11.2.4 Incremental Relaying 312  
11.2.5 Two-Way Relaying 313  
11.2.6 Other Enhancements 317  
11.3 Resource Allocation for Single-Carrier Systems 318  
11.3.1 Power Allocation for AF Relaying 318  
11.3.2 Power Allocation for Selection AF Relaying 320  
11.3.3 Joint Relay Selection and Power Allocation for ANC Two-Way Relaying 321
Contents

11.4 Resource Allocation for Multi-Carrier Systems

11.4.1 Resource Allocation for AF Multi-Carrier Wireless Networks

11.4.2 Resource Allocation for DF Multi-Carrier Wireless Networks

11.4.3 Resource Allocation for Multi-User ANC Two-Way Relay Networks

11.5 Further Discussion

11.6 Exercises

References

12 Channel Allocation for Infrastructure-Based 802.11 WLANs

12.1 Introduction

12.2 System under Consideration

12.2.1 Network Topology

12.2.2 Channelization

12.2.3 Medium Access Control

12.3 Channel Assignment and AP Placement in IEEE 802.11 WLANs

12.3.1 Channel Assignment

12.3.2 AP Placement

12.4 Challenges in Channel Assignment in IEEE 802.11 WLANs

12.5 Channel Assignment Schemes in Centrally Managed Environments

12.5.1 Channel Assignment with AP Placement

12.5.2 Channel Assignment without AP Placement

12.6 Channel Assignment Schemes in Uncoordinated Environments

12.6.1 Least Congested Channel Search (LCCS)

12.6.2 MinMax Approach

12.6.3 MinMax II Approach

12.6.4 Hminmax/Hsum: Weighted Coloring Approach

12.6.5 Pick-Rand and Pick-First Approach

12.6.6 Pick-Rand and Pick-First II Approach

12.6.7 Channel Hopping Approach

12.6.8 Measurement-Based No-Coord

12.7 Comparison among Various Channel Assignment Schemes

12.8 Current Practice in Channel Assignment

12.9 Open Research Issues

References

Part V Cross-Layer Modeling for Resource Allocation in Wireless Networks

13 Joint PHY/RLC Design in Cellular Wireless Networks

13.1 Introduction

13.2 Radio Link Control (RLC) Protocols: ARQ and HARQ

13.3 Link Adaptation with Adaptive Modulation and Coding (AMC)
## Contents

13.4 Channel Modeling
   13.4.1 I.I.D. Channel Models 383
   13.4.2 Two-State Markov Channel Model 383
   13.4.3 Finite-State Markov Channel Model 386

13.5 ARQ Protocols with I.I.D. Errors 386

13.6 ARQ Protocols in Two-State Markov Channel 388
   13.6.1 GBN-ARQ Protocol in Two-State Markov Channel 389
   13.6.2 SR-ARQ Protocol in Two-State Markov Channel 391

13.7 Truncated ARQ Protocol with Link Adaptation under I.I.D. Channels 392

13.8 Delay Analysis of GBN-ARQ Protocol with Link Adaptation under FSMC 393
   13.8.1 System and Protocol Description 394
   13.8.2 Queuing Model 395
   13.8.3 Derivations of Matrix Blocks in (13.57) 397
   13.8.4 Delay Analysis 400
   13.8.5 Numerical Example 401

13.9 Hybrid ARQ Protocol with Transmission Size Adaptation 402

13.10 Exercises 405

References 412

Index 415
Preface

Wireless communications and networking technology are advancing at a very rapid pace. Newer technologies and standards are evolving to serve the ever-increasing number of users demanding different types of mobile applications and services. Research and development activities on wireless technology constitute one of the most important segments of research and development in the telecommunications area today. Radio resources such as the radio spectrum and transmission power are the fundamental ingredients for any wireless system. Radio resource management is a fundamental problem in wireless networks. Efficient allocation and management of radio resources to serve the mobile users with different requirements is essential for practical deployment and operation of wireless communications systems and networks.

Radio resource allocation is a very broad topic that cannot be fully covered in a single book. This book with the title *Radio Resource Management in Wireless Networks: An Engineering Approach* particularly focuses on resource management issues related to power control, interference management, joint power control and cell association, channel assignment, and multiple access control in traditional as well as emerging wireless networks such as multi-tier cellular, relay-based cellular, and cognitive radio networks (CRNs). This book intends to provide background knowledge on resource allocation in wireless networks from a system-centric or engineering point of view, review the existing related literature, discuss the research challenges, present different techniques to model and analyze the resource allocation problems, and develop both centralized or distributed resource allocation algorithms. This book includes the classical as well as recently developed models and analyses for allocation of different resources (e.g., spectrum and transmission power) in cellular wireless networks. It will be useful for graduate students (M.Sc. and junior Ph.D. students) to understand different resource allocation problems and algorithms in different types of wireless networks (i.e., both infrastructure-based and infrastructure-less wireless networks). It can be used as a textbook for a graduate course on “Wireless Networks” as well as a reference book for researchers and engineers working in the area of wireless communications and networks.

Graduate students who intend to work in this area need to familiarize themselves with the basic concepts of resource management (e.g., power control, channel allocation, error control) in wireless networks and the related mathematical models. The majority of currently existing textbooks on Wireless Communications/Mobile Networks focus on the physical layer (PHY) aspects of wireless communications and do not provide an
Preface

in-depth treatment of the resource allocation as well as medium access and radio link control problems in wireless networks. This book intends to fill in this gap and cover the state-of-the-art of research and development in this area. This book can serve as a quick reference for major radio resource management issues in wireless networks as well as related mathematical models for analysis and optimization of radio resource management techniques.

The key features of this book are as follows:

- A systematic view looking at resource management problems in wireless networks that will help readers to classify and compare different types of problem formulations and extend the existing modeling approaches and solution concepts to new system models;
- A comprehensive review of the state-of-the-art research on major resource management problems (e.g., channel and power allocation, error control) in wireless networks;
- Coverage of a wide range of techniques from optimization and game theory (along with examples) for design, analysis, and optimization of resource allocation methods in wireless networks;
- Examples and practice problems (exercises) on different resource management problems;
- Outlines for the key research issues related to resource management in wireless networks.

We have organized the book into the following parts.

Part I: Basics of Wireless Networks
In Chapter 1, starting with an introduction to wireless communications (including signal characterization and modulation, radio propagation and channel models for wireless packet communications), different wireless access technologies (e.g., cellular wireless, wireless local area network [WLAN], wireless metropolitan area network [WMAN], and wireless personal area network [WPAN] technologies) are briefly reviewed. Issues related to medium access control in wireless networks are also discussed.

In Chapter 2, basics of protocol layers for data communication, categorization of different wireless networks, and the fundamentals of modeling and analysis of different physical and radio link layer techniques (including different digital transmission and smart reception techniques, multiple access, scheduling, error control, power control, cell association, handoff management and admission control methods) are discussed. Also, a high-level taxonomy of research areas related to resource management in wireless networks is presented.

Part II: Techniques for Modeling and Analysis of Radio Resource Allocation Methods in Wireless Networks
This part presents different techniques, which can be applied to model and analyze the resource allocation problems in wireless networks. In Chapter 3, optimization techniques are discussed. Major variations of optimization techniques (e.g., unconstrained
Part III: Physical Layer Resource Allocation in Wireless Networks

This part deals with the distributed power control and user association problems in wireless networks. Chapter 5 presents the system model, notations, basic definitions, and relationships related to uplink and downlink power control in interference-limited cellular networks. Both single-cell and multi-cell scenarios are considered. This chapter provides the basics to understand the materials presented in the subsequent chapters of this part of the book.

Starting with a discussion on the motivations of power control, Chapter 6 discusses the conventional open-loop, closed-loop, and centralized power control methods. Then it discusses different existing power control algorithms for homogeneous (single-tier) wireless cellular networks. In this context, different objectives of distributed power control (e.g., aggregate transmit power, system throughput, and outage ratio) are discussed. The existing power control algorithms are compared in terms of different criteria such as fixed-point existence and uniqueness, convergence, rate of convergence, objective functions, and implementation complexity in terms of signaling overhead.

Chapter 7 deals with the joint distributed power and admission control problem in cellular networks. The existing methods for joint admission and power control are discussed, and the state-of-the-art results are summarized.

Chapter 8 deals with the joint power and admission control problem in underlay CRNs, where primary users have a higher priority than secondary users while accessing the radio spectrum. Different optimization models for this problem are introduced, the feasible interference regions for the primary users are characterized, and the existing algorithms for centralized joint power and admission control are reviewed. To this end, two algorithms are presented for joint power and admission control in CRNs.

Chapter 9 deals with the distributed cell association problem (also called the user association problem) in cellular networks. The existing methods for distributed cell association are reviewed, and the problem of distributed joint cell association and power control is studied. Also, methods for generalizing the existing distributed power control algorithms to joint power control and base station (BS) assignment algorithms are discussed.

Part IV: Link Layer Resource Allocation in Wireless Networks

Chapter 10 provides an overview of the channel allocation methods in multi-carrier (e.g., orthogonal frequency division multiple access [OFDMA]) networks. Also, some open research issues are discussed.
Preface

Chapter 11 deals with the resource allocation problem in cooperative (e.g., relay-based) networks. The fundamental aspects of cooperative protocols and resource allocation methods for single and multi-carrier relaying networks are presented.

Chapter 12 presents a survey on the channel allocation methods for wireless local area networks (WLANs). A qualitative comparison among the different methods is made and current practices in channel allocations are discussed. Several open research directions in this area are also outlined.

Part V: Cross-Layer Modeling for Resource Allocation in Wireless Networks

Chapter 13 discusses important models for performance analysis and cross-layer (e.g., physical-link) design of radio link level error control methods. In particular, it covers the fundamental aspects of analysis and design of automatic repeat request (ARQ) and hybrid ARQ (HARQ) protocols considering wireless channels with different characteristics.